

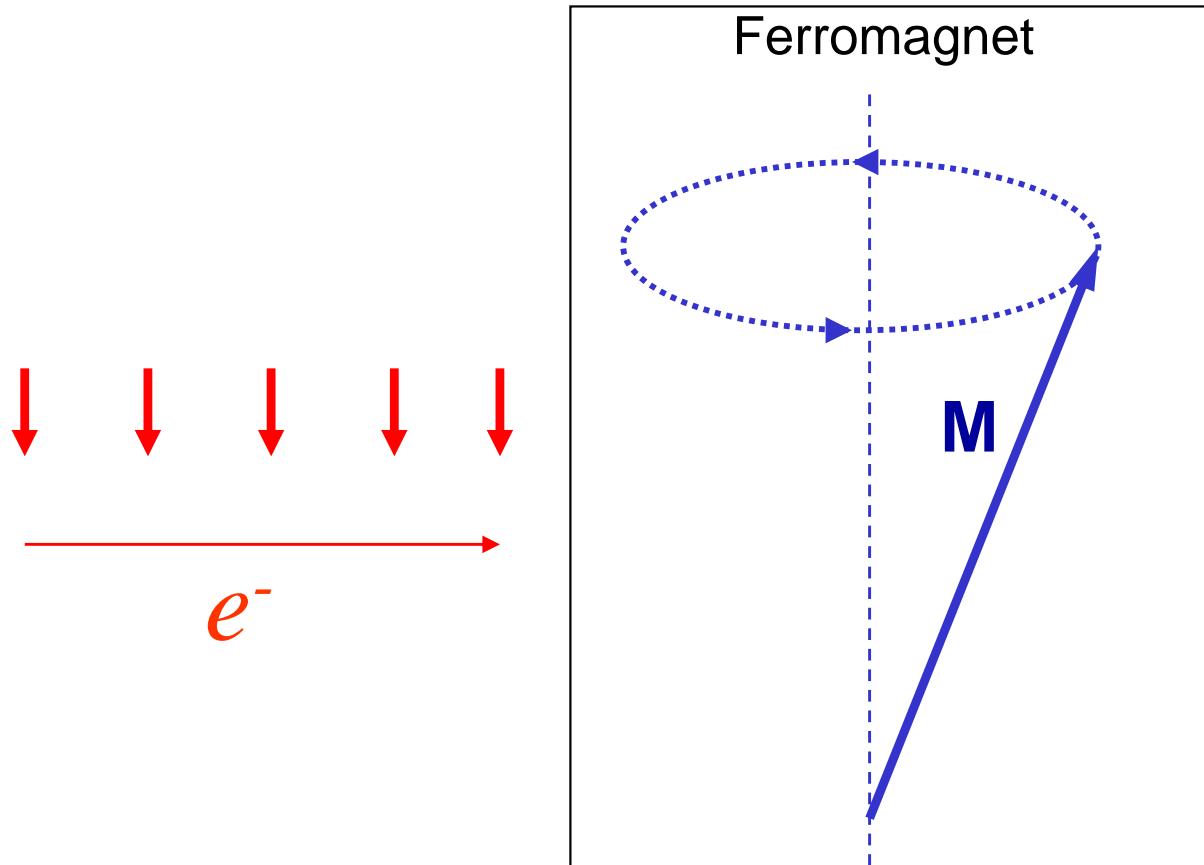
Spin Transfer in Nanomagnets

I. Krivorotov

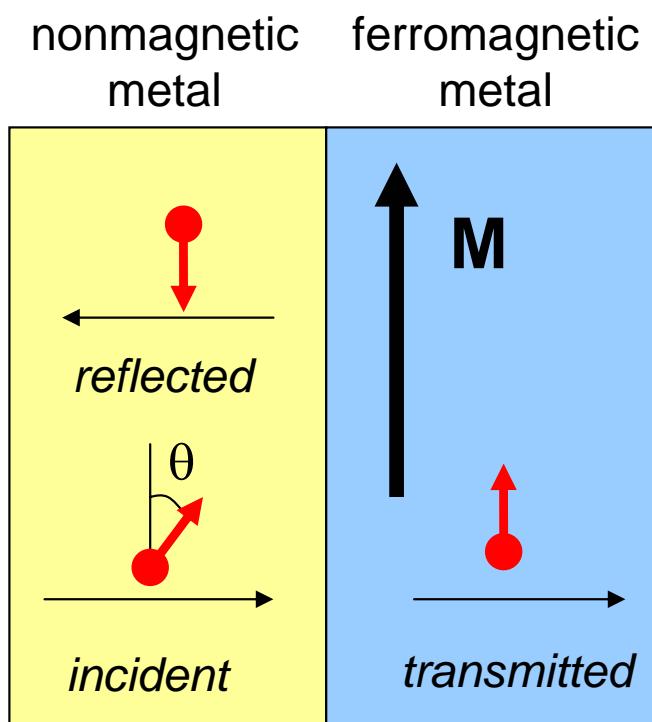
University of California, Irvine

N. Emley, J. Sankey, S. Kiselev, D. Ralph, R. Buhrman

Cornell University



Spin-Dependent Scattering and Spin Transfer

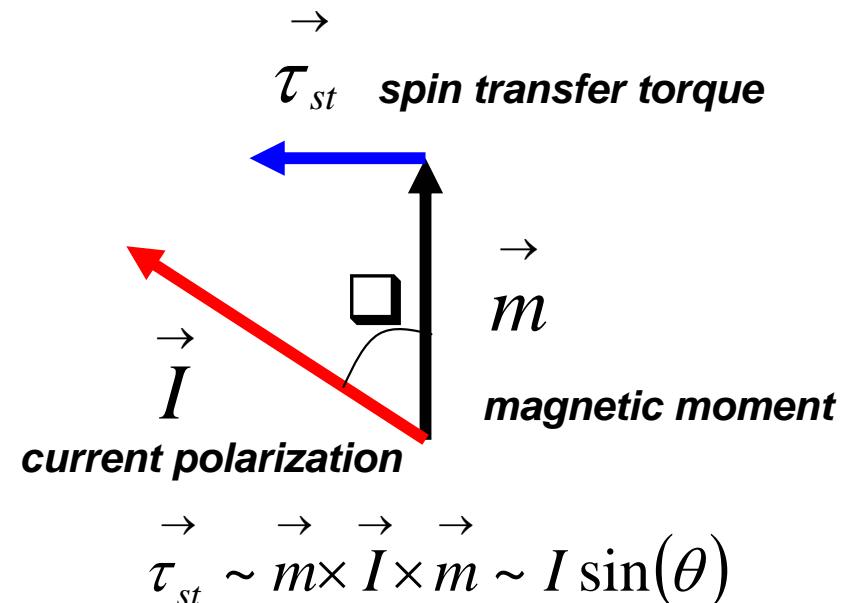


Slonczewski, JMMM (1996)

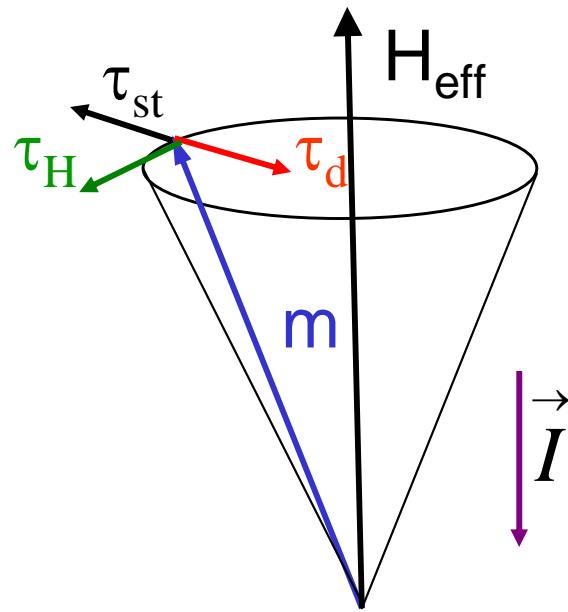
Stiles and Zangwill, PRB (2002): for realistic band structures of many transition metal pairs (e.g. Co/Cu), the **component of spin current perpendicular to magnetization** is almost completely absorbed by the ferromagnet.

electron wavefunctions		
incident	reflected	transmitted
$\psi_{in} \sim \begin{pmatrix} \cos\left(\frac{\theta}{2}\right) \\ \sin\left(\frac{\theta}{2}\right) \end{pmatrix}$	$\psi_{ref} \sim \begin{pmatrix} R_\uparrow \cos\left(\frac{\theta}{2}\right) \\ R_\downarrow \sin\left(\frac{\theta}{2}\right) \end{pmatrix}$	$\psi_{tr} \sim \begin{pmatrix} T_\uparrow \cos\left(\frac{\theta}{2}\right) \\ T_\downarrow \sin\left(\frac{\theta}{2}\right) \end{pmatrix}$

If interfacial scattering is spin-dependent ($T_\uparrow \neq T_\downarrow$ and $R_\uparrow \neq R_\downarrow$) then both transmitted and reflected electrons rotate the direction of their spin, and angular momentum may be transferred to magnetization of the ferromagnet.



Magnetization Dynamics due to Spin Transfer Torque

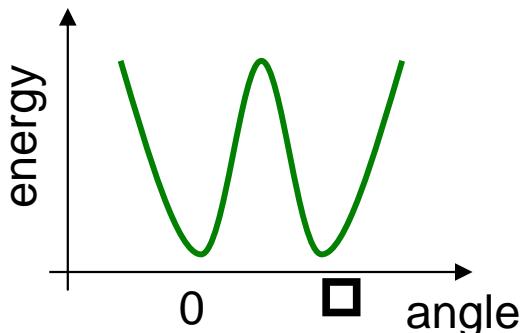


τ_H – field torque

τ_d – damping torque

τ_{st} – spin transfer torque

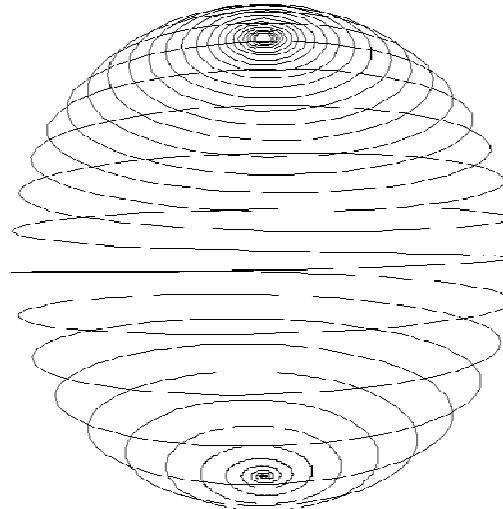
Uniaxial ferromagnet



LLG
equation

$$\frac{d\vec{m}}{dt} = -\gamma \cdot \vec{m} \times \vec{H}_{\text{eff}} + \frac{\alpha}{|\vec{m}|} \cdot \vec{m} \times \frac{d\vec{m}}{dt} + \eta \cdot \vec{m} \times \vec{I} \times \vec{m}$$

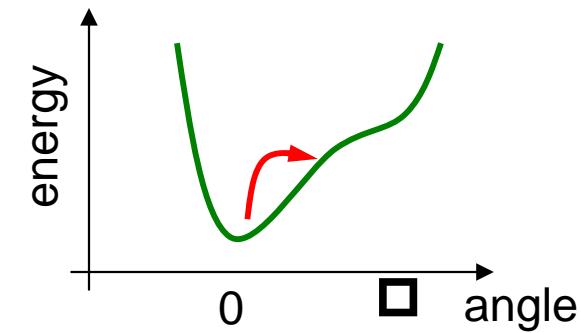
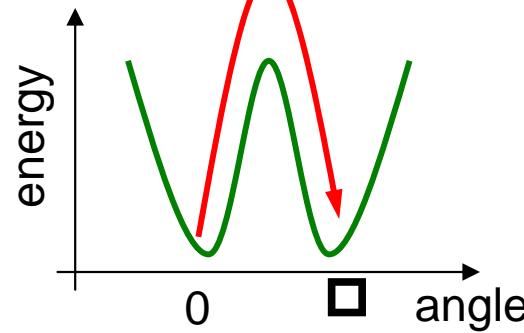
switching



persistent precession

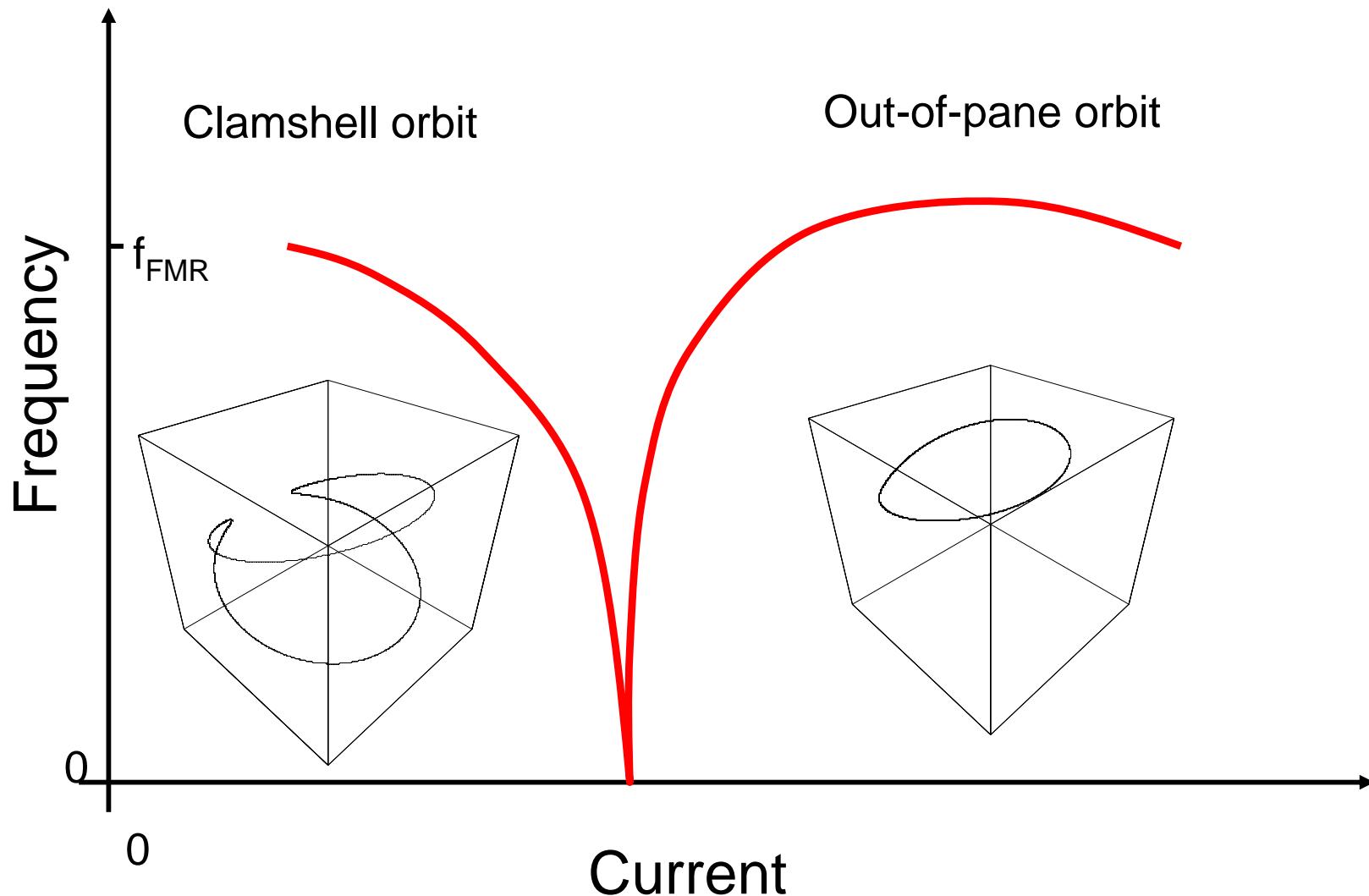
H_C – anisotropy field

$H > H_C$



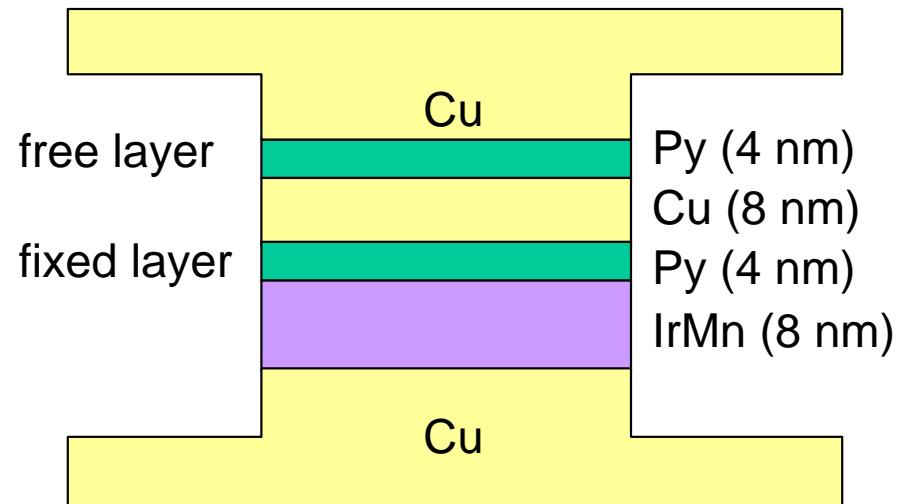
LLG + Spin Torque Macrospin Predictions for Dynamics

Thin-film nanomagnet (easy axis+ easy plane anisotropies), $H > H_C$

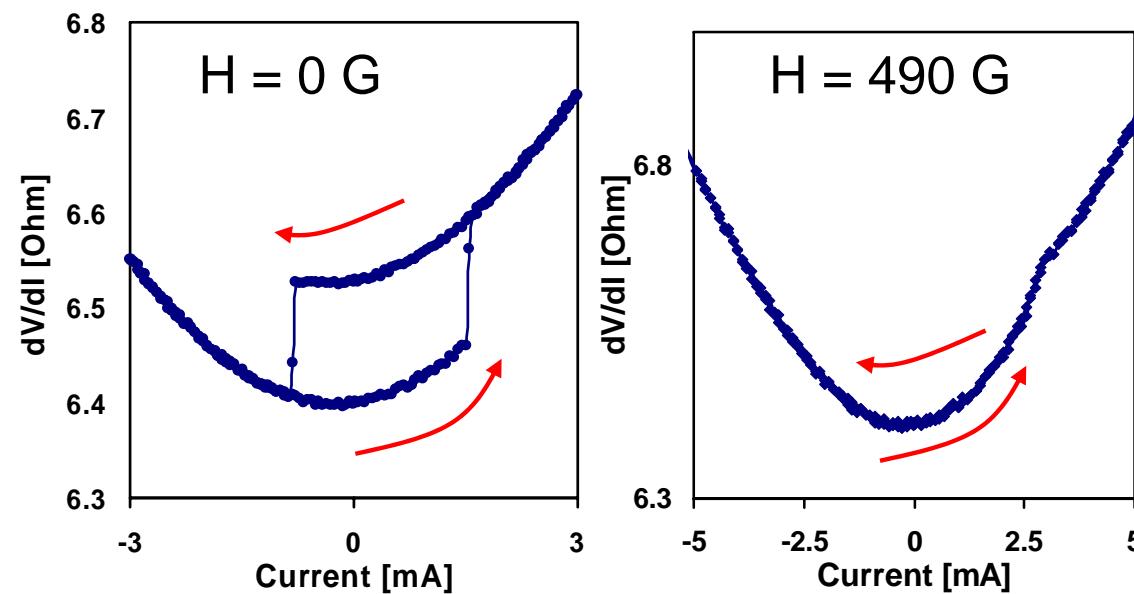
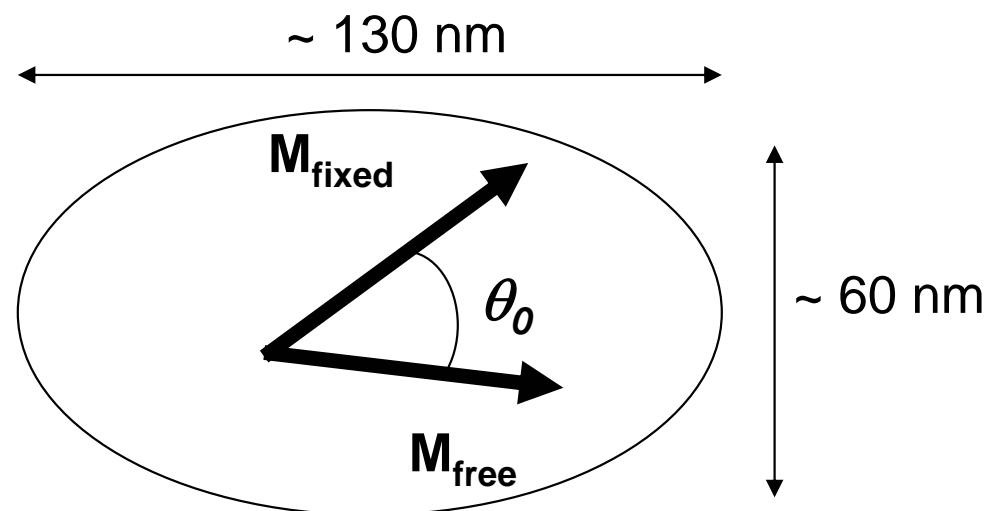


Nanoscale Spin Valves for Spin Transfer Studies

Side view



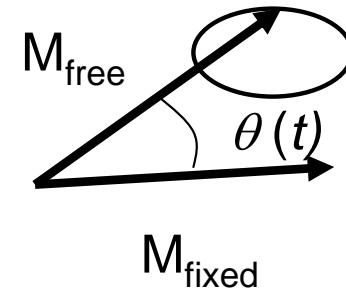
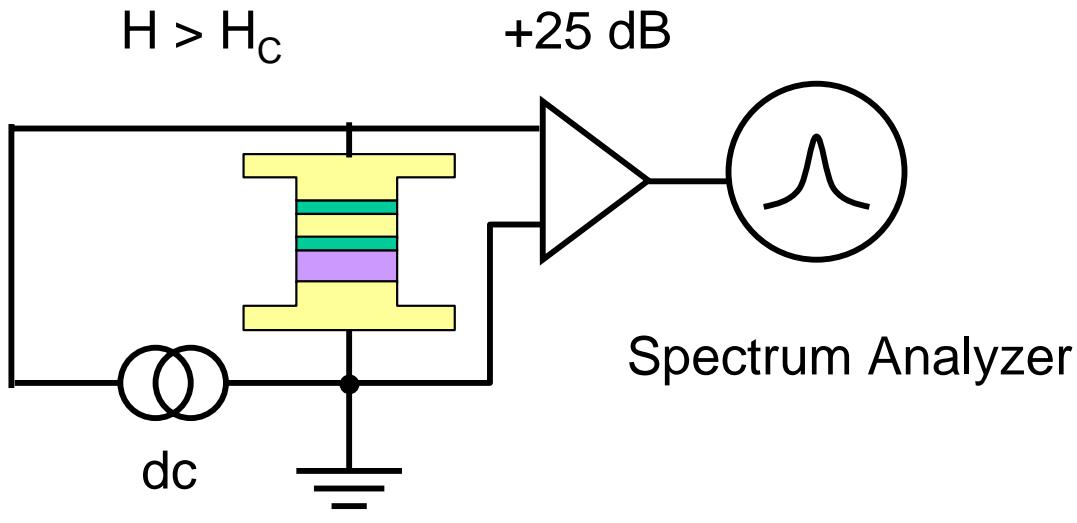
Top view



$\downarrow H_{\text{applied}}$

- Spin torque magnitude $\sim \sin(\theta)$, where θ is the angle between current polarization and magnetization
- Devices with non-zero equilibrium θ are used to maximize spin torque and to give well-defined phase of motion of magnetization

Measurements of Magnetization Dynamics: Frequency Domain

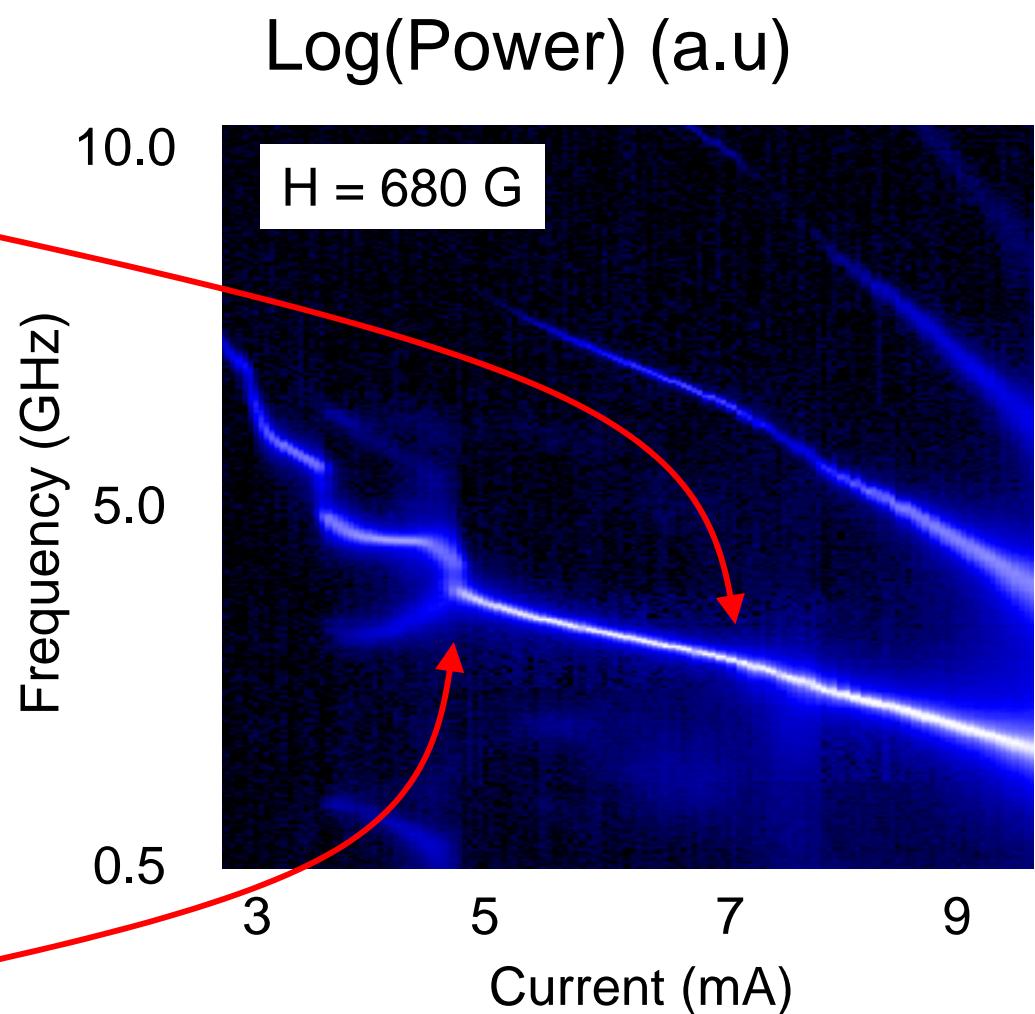
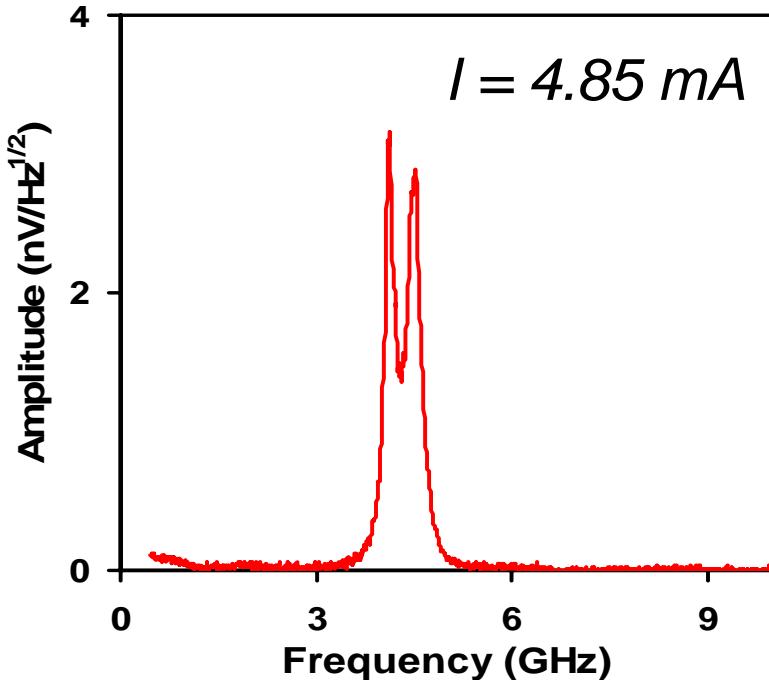
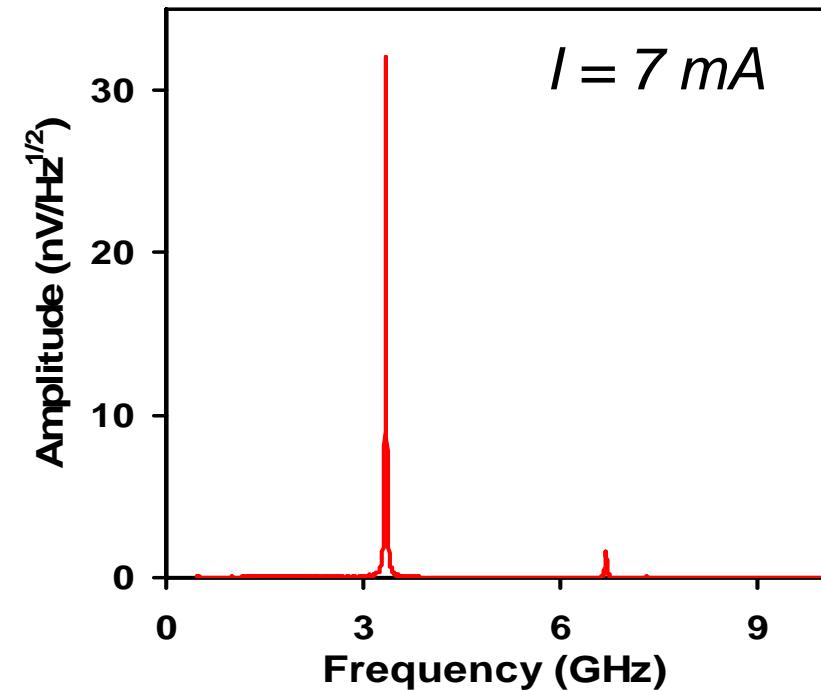


$$V(t) = I \cdot R(\theta(t))$$

To suppress thermal fluctuations of magnetic moment, measurements are made at $T = 5 - 40$ K.

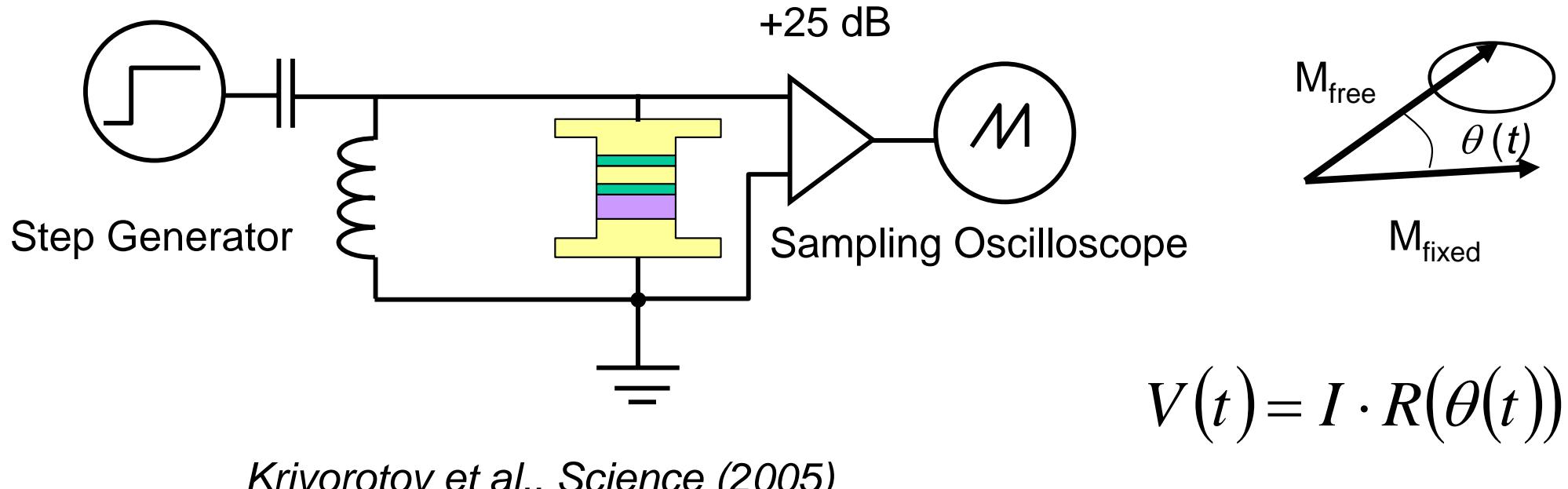
1. Direct current excites motion of the free-layer magnet.
2. Resistance of the sample varies in time due to moving magnetization via GMR.
3. Since the device is current-biased, ac voltage is generated by the device.

DC – Driven Auto-oscillations of Magnetization



- Coherent precession of magnetization
- Frequency red-shifts with current
- Multiple magnetic modes excited

Measurements of Magnetization Dynamics: Time Domain

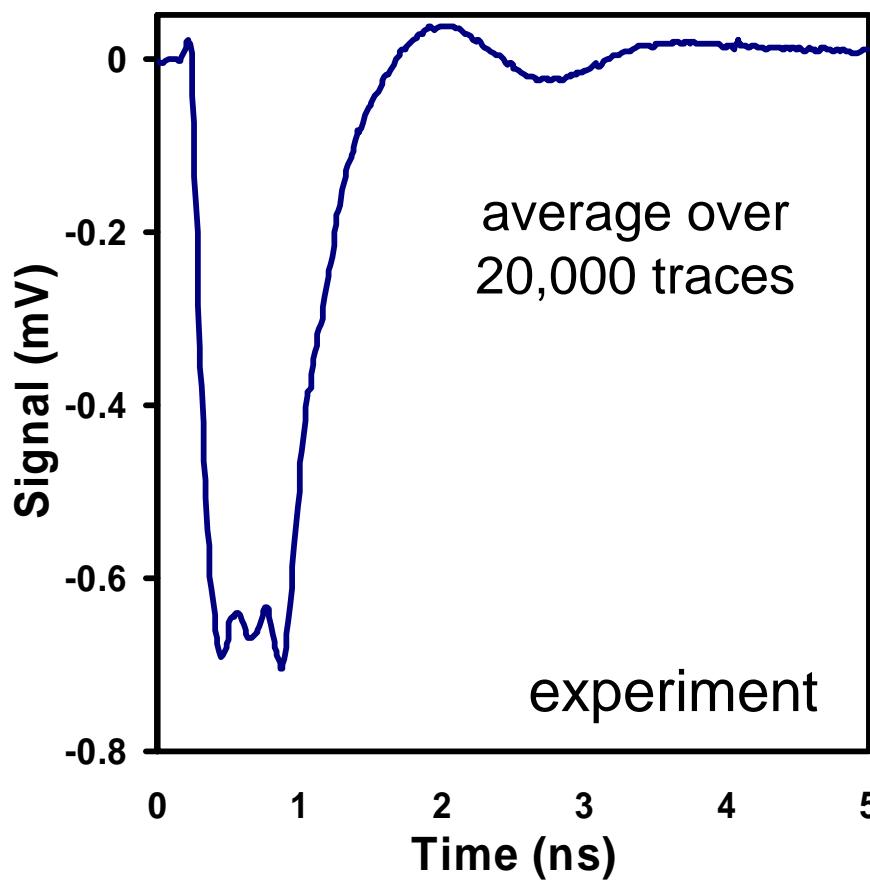


Krivorotov et al., Science (2005)

- Current step applied to the nanopillar excites magnetization dynamics.
- Stroboscopic measurement of the transmitted signal
- After a background subtraction procedure, voltage measured by the oscilloscope is proportional to resistance of the device.

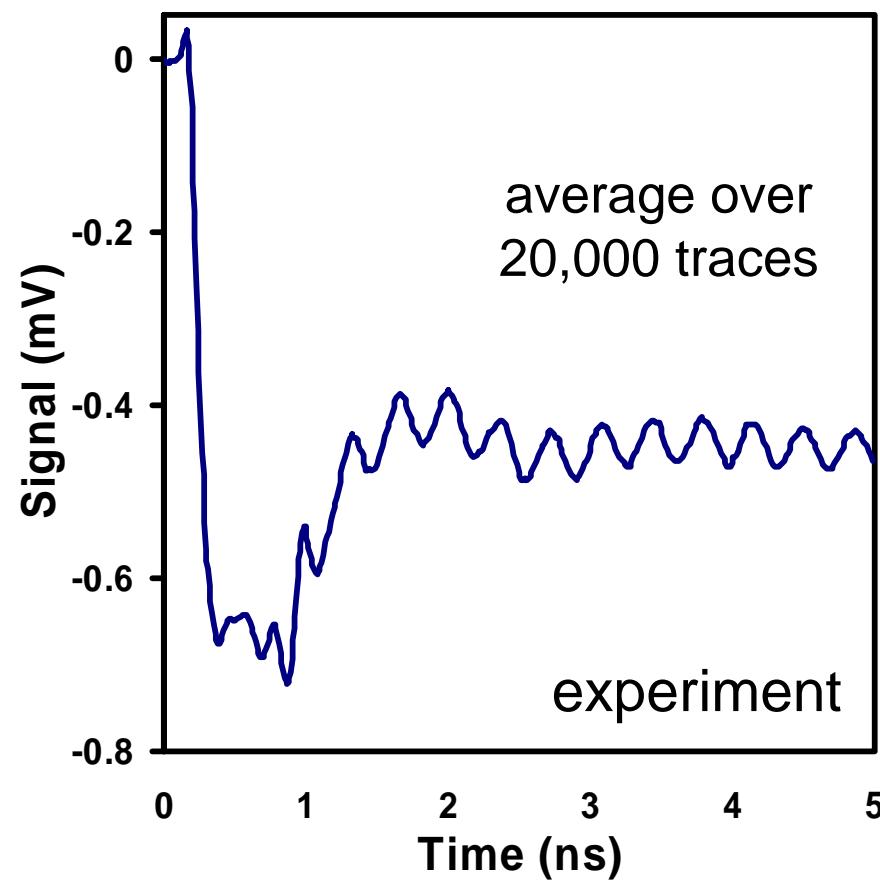
Time Resolved Measurements – Response to a Current Step

$H = 450 \text{ G} < H_c$



High resistance state

$H = 680 \text{ G} > H_c$

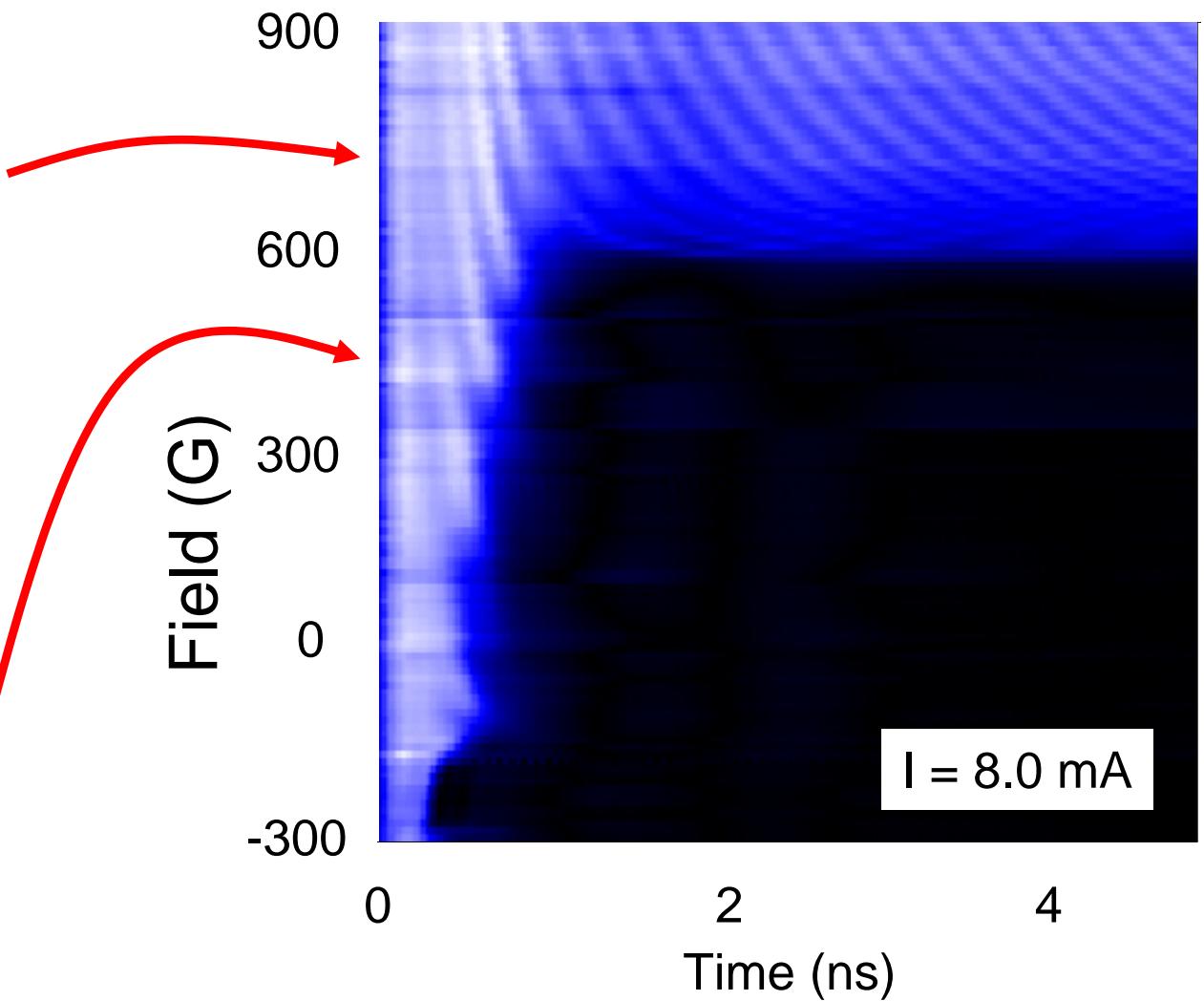
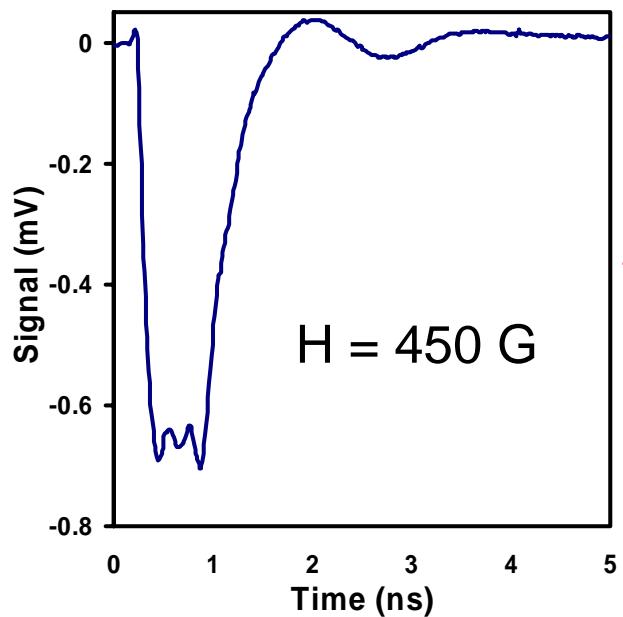
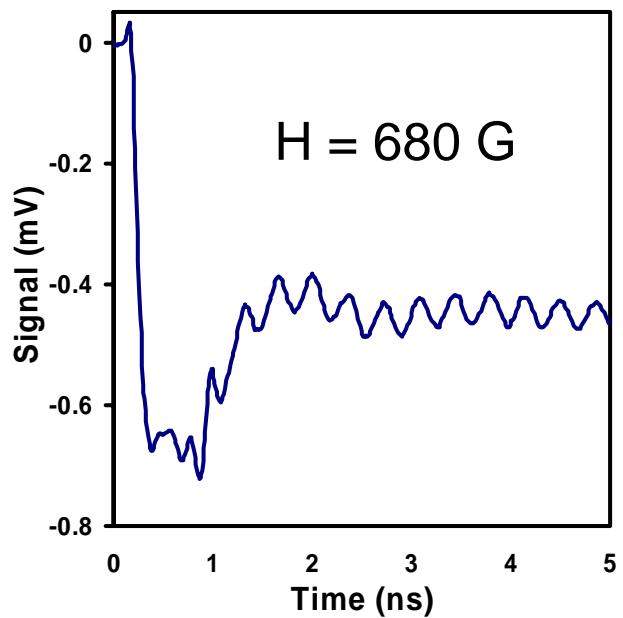


$I = 8.0 \text{ mA}$

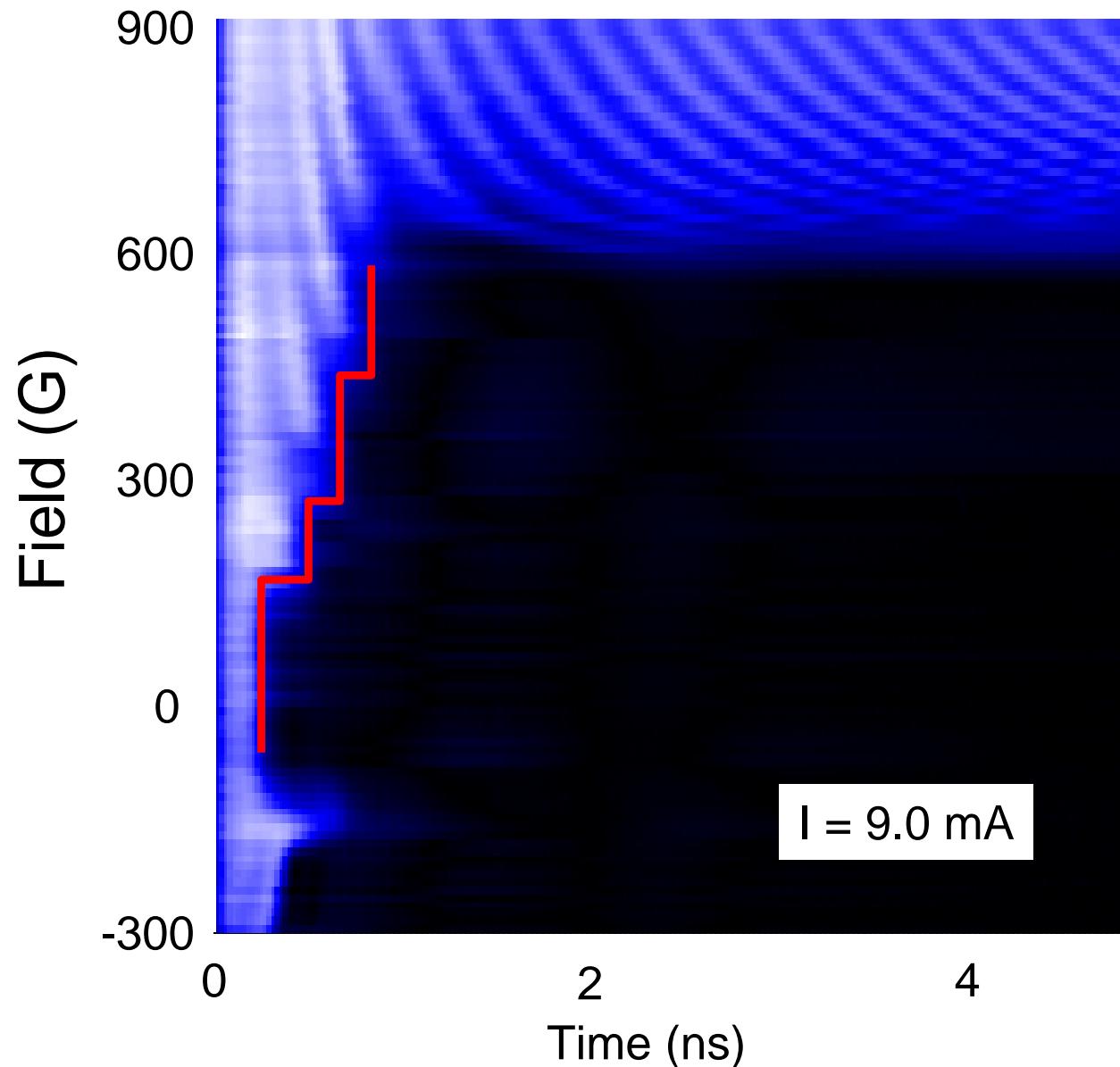
$T = 4.2 \text{ K}$

Low resistance state

Transition between Switching and Precession

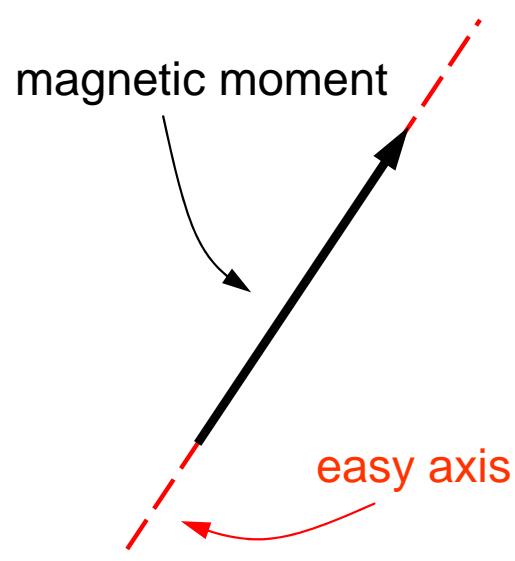


Switching Time versus Field



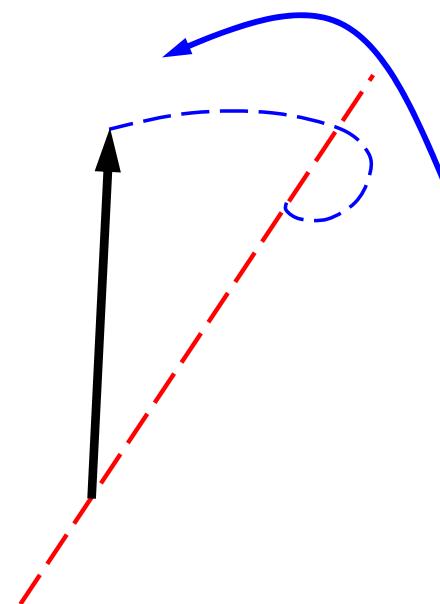
Relaxation of Magnetization in Presence of Spin Current

1. Equilibrium



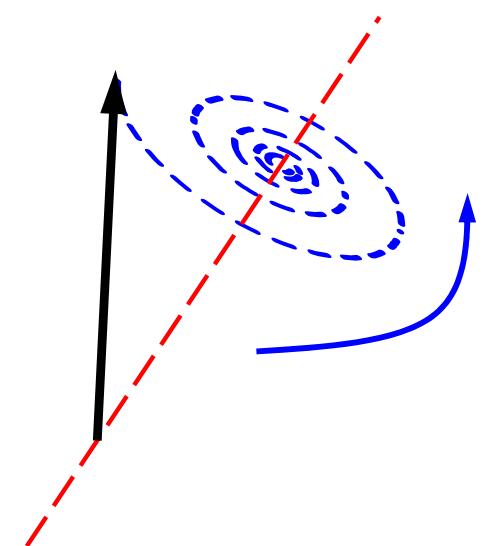
$$I < I_c$$

2. Excitation



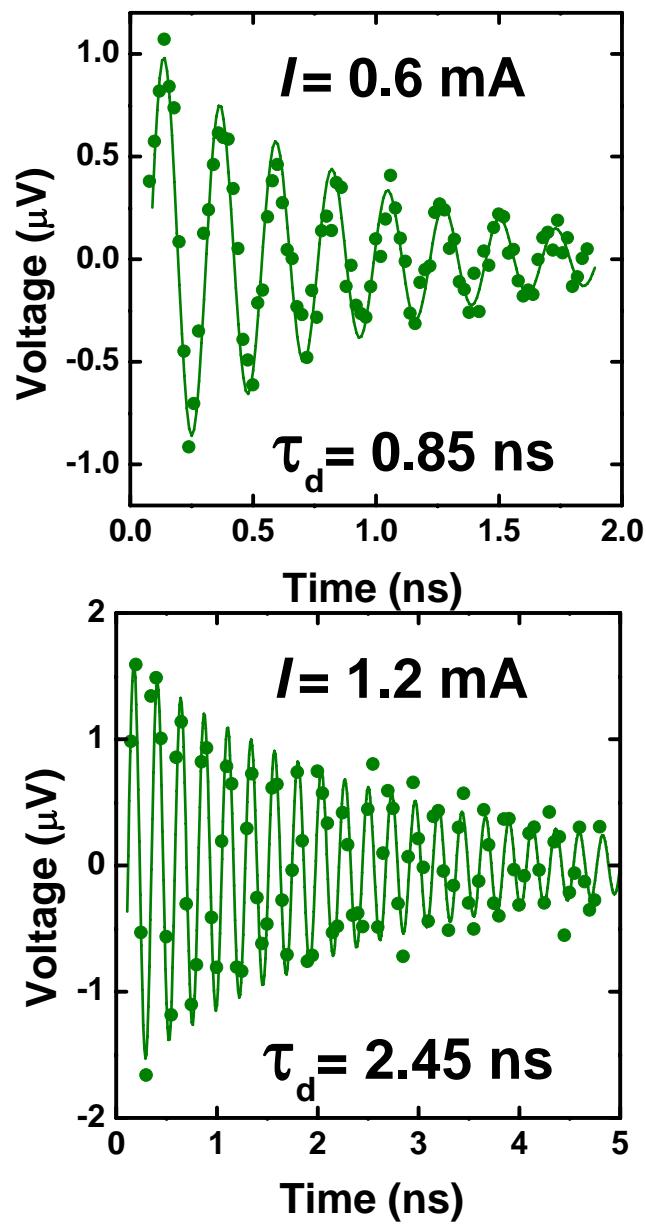
short current
pulse with $I > I_c$

3. Ring-down

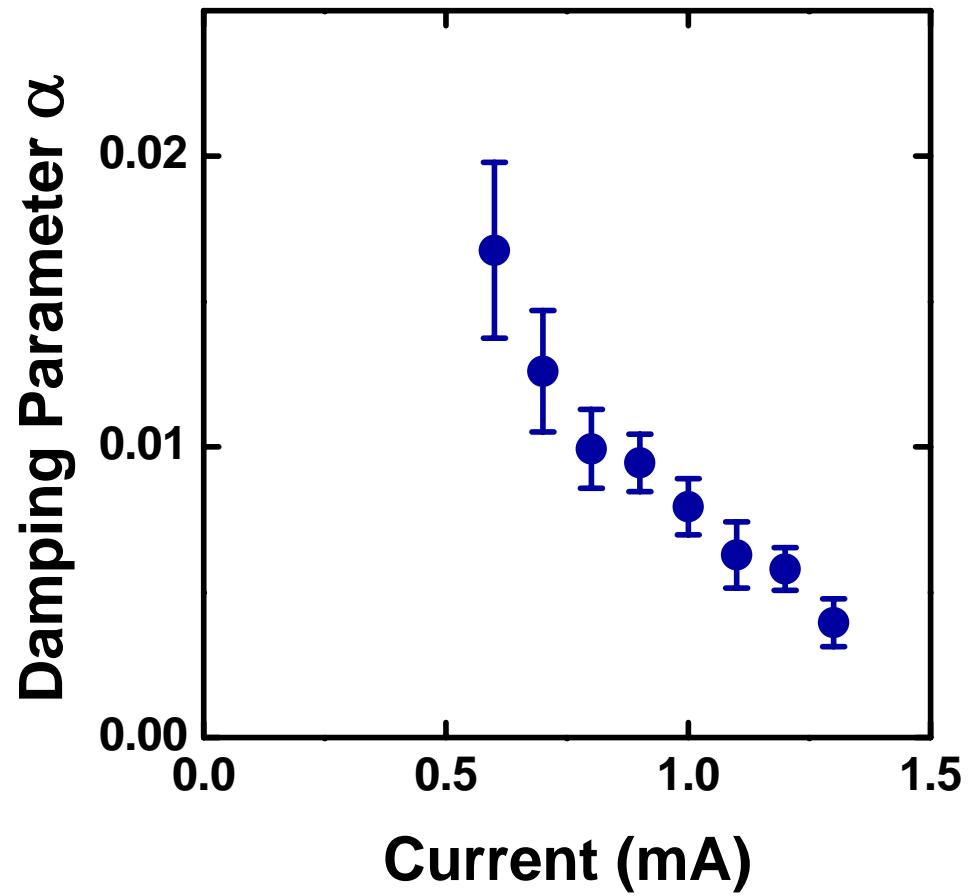


$$I < I_c$$

Gilbert Damping Parameter versus Bias Current



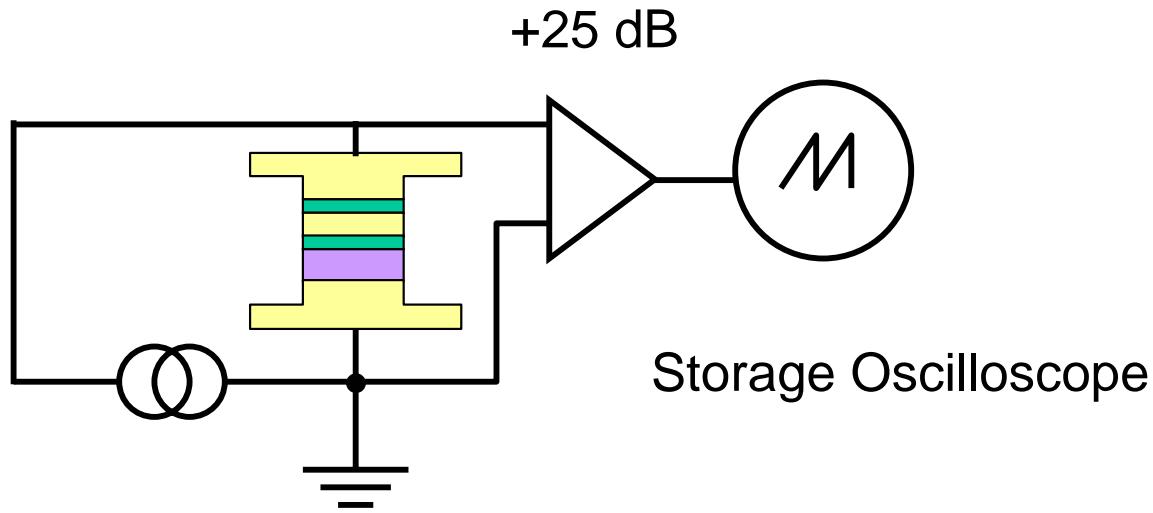
● - data
— - fit



$$\alpha = \frac{2}{\tau_d \gamma \mu_0 M_s}$$

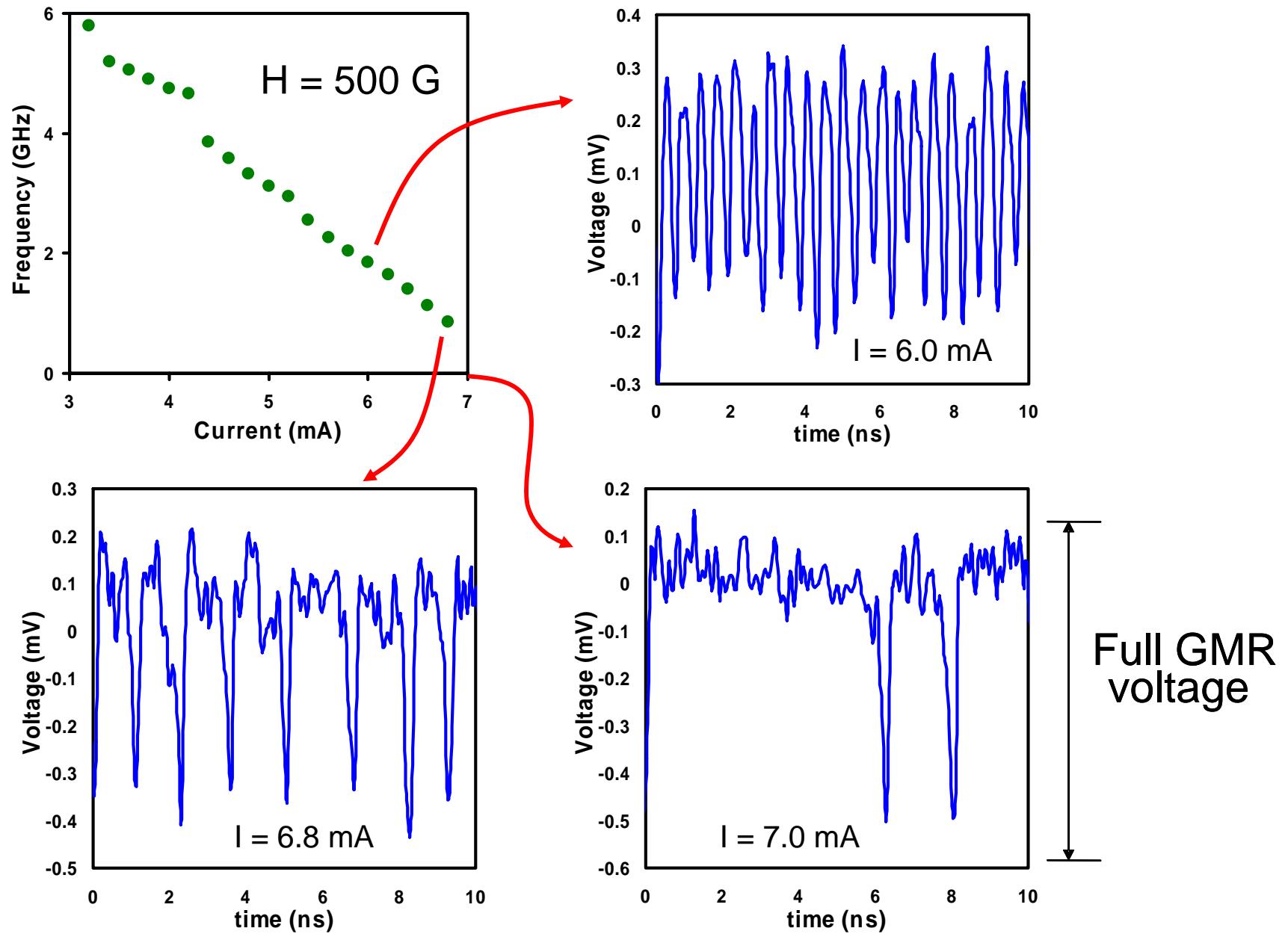
τ_d – decay time
 γ – gyromagnetic ratio
 M_s – saturation magnetization

Time Domain Measurements with Storage Oscilloscope



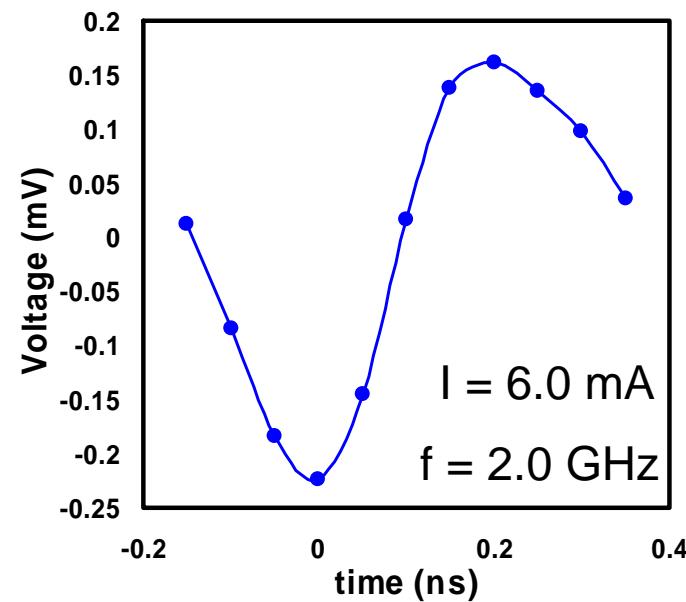
Real time voltage traces of persistent dynamics can be measured

Low Frequency Dynamics: Single Trace

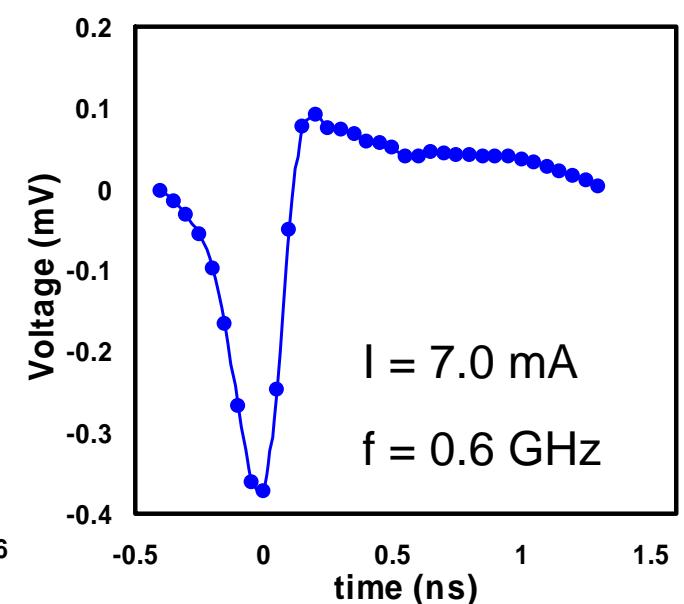
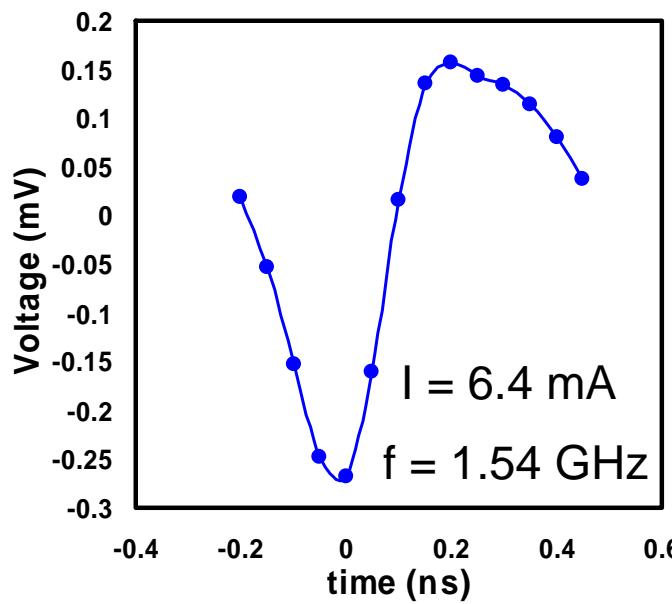


Low Frequency Dynamics: Single Period

$H = 500 \text{ G}$



triggering on the signal itself, averaging



-“Slow” current-driven dynamics:

large amplitude
very non-linear
stochastic

Conclusions

- Experiments on current-driven magnetization dynamics are qualitatively consistent with the spin torque model:
 - persistent coherent autooscillations above the critical field
 - precessional switching for subcritical field
 - renormalization of Gilbert damping parameter by subcritical current
- Deviations from macrospin model of current-driven magnetization dynamics:
 - multiple magnetic mode excitation
 - metastable static states at high current
 - detailed comparison with micromagnetic simulations is needed
- Very large amplitude of motion of magnetization can be achieved with spin torque. This opens new opportunities for studies of magnetization dynamics in highly non-linear regimes (e. g. fate of Suhl instability in a nanomagnet ?, origins of magnetic dissipation in ferromagnetic metals ?)